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Title - "Combustor/Inlet Interactions and modeling of Hypersonic Dual Combustion Ramjet Engines"

Author - Paul J. Waltrup

Grant # - AFOSR-MIPR-83-00005

SUMMARY

Two distinct but related basic research efforts are being investigated under the joint sponsorship of the U.S. Air Force Office of Scientific Research (AFOSR) and the U.S. Naval Sea Systems Command (NAVSEA). The first effort is to experimentally characterize the flowfields at the entrance of supersonic combustors in hypersonic dual-combustion ramjet engines and the second is to develop the component and engine cycle analysis required to predict the internal flowfields and performance of these engines. Both are basic to the successful development of advanced, hypersonic airbreathing engines. Air Force funding for these efforts is $75K in GFY 1983.

Progress to date includes the development of a simplified axisymmetric mixing and combustion analysis and a concomitant wall boundary layer analysis which describe the major flow phenomena within the main supersonic combustor of a dual combustion ramjet engine. The experimental hardware for the combustor/inlet interaction tests is also complete and initial testing has begun. Currently, refinements to the combustion and wall boundary layer analysis with particular emphasis on the base flow/mixing region, are being pursued and testing with the combustor/inlet interaction hardware continue.

INTRODUCTION

Requirements for future offensive and defensive weapon systems necessitate the development of long range, very high speed missiles to effectively counter the continually improving capabilities of similar systems by potential hostile nations. Of the candidate propulsion cycles available to power these missiles, only rockets and advanced ramjets employing supersonic combustion as their primary mode of combustion are capable of providing the hypersonic speeds required. However, rockets must fly exo-atmospheric trajectories to achieve the needed ranges and, since they are coasting, their ability to make corrections and to intercept maneuvering targets is limited. On the other hand, advanced hypersonic ramjets, which remain within the atmosphere, are capable of sustained powered flight, course changes, and interception of maneuvering targets. The need for advanced hypersonic ramjets is, therefore, apparent. However, in order to develop these engines under exploratory and advanced development programs requires a basic understanding of the engine and individual component flowfields and thermochemistry, viz., in the inlet, air duct, fuel injectors/combustor(s) and exit nozzle. This basic understanding comes from analytical models of the engine and its components and concomitant experiments.

AFOSR-TR- 89-1601

RELEVANCE

This effort is jointly funded by AFOSR and NAVSEA. Its intent is to develop an understanding of the basic fluid dynamics, thermochemistry, heat transfer, etc. mechanisms which are indigenous to hypersonic air breathing ramjet engines. The results obtained will be applicable to the future hypersonic engine requirements of not only the U.S. Air Force and Navy but other government agencies as well. Currently the results of this research are being applied in the hypersonic engine development programs being pursued by NAVSEA and NASA.

APPROACH

The approach taken here is twofold. The first is experimental in nature and limited to one area of an advanced, dual-mode hypersonic ramjet (Ref. 1) such as that shown schematically in Fig. 1, i.e., the combustion induced, shock-separated region at and upstream of the entrance of the supersonic combustor. Specifically, this effort will experimentally characterize the flowfield in this region over a wide range of test conditions and provide the details needed to better understand the complex shock/boundary layer interactions which occur. These data will then be used to develop a semi-empirical model of the interaction region. The second approach is an analytical effort in which models of the dual-combustion process and overall engine cycle will be developed and compared with the available experimental data. The former will enhance the understanding of the details of the combustion process, such as flow profiles, wall skin friction, wall heat transfer and chemical kinetics, while the latter will provide fundamental global predictive techniques for the overall engine and parametric variations thereof.

BACKGROUND

Combustor-Inlet Interaction (CII) Tests and Modeling: In the development of scramjet engines, experimental data in both connected-pipe(Ref. 2) and free-jet tests (Ref. 3) have shown that provisions must be made to isolate the combustion-induced pressure disturbances situated at the entrance of the combustor from interacting with the compression field of the air inlet. The flow in this region can be characterized as a non-uniform, shock-separated flow and pure analytical-techniques are not available to predict this flow structure with any degree of certainty. Consequently, a semi-empirical approach combining experimental data with a correlative analysis is needed in order to predict the required length of isolator (Ref. 4).

An experimental technique shown in Figure 2 and described in Refs. 5-7 has been used to determine a correlating parameter for the design of conventional scramjet engines (e.g., the SCRAM engine configurations). A shock structure was established in a cylindrical duct in unheated supersonic flow by use of a throttling valve. Measurements were made to obtain the pressure distribution and shock structure and a correlating parameter was obtained that adequately described the axial pressure distribution as a function of shock strength for all shock pressure rises lower than that corresponding to a normal shock.

The geometry, flow conditions and method of fuel injection in dual-combustion ramjet (DCR) engines are, however, so significantly different from conventional scramjet engines that it is necessary to develop a new experimental base to determine a new or revised correlating parameter. The current tests are being made in the coaxial setup, consisting of a supersonic annulus surrounding a sonic core, which is shown schematically in Fig. 3. Tests will be made at three Mach numbers (1.75, 2.5 and 3.0) in the supersonic annulus and for shock strengths from weak oblique to normal. The pressure and momentum ratios of the jets could also be important governing parameters and could affect the flow at the exit of the gas generator, so these ratios are also varied. Once a correlating parameter is derived, its validity will be tested by comparison with pressure distribution results from direct-connect tests of full-scale dual combustors (see, e.g., Ref. 8).

<u>Component and Engine Cycle Modeling</u>: Although individual component and overall engine cycle analyses have been developed to the point of being useful models for conventional scramjet engines (see, e.g., Refs. 9-12), modifications and/or extensions to these analyses as well as new analyses are needed to model the more complex DCR tandem combustor configuration and overall engine cycle. Currently, models of the dual-combustion (subsonic/supersonic) combustor used in the DCR engine continue to be developed and refined and, ultimately, will be married with an overall engine cycle analysis such as that outlined in Ref. 1. The combustor analyses include integral models as well as multidimensional mixing and combustion models and combinations thereof.

Each technique has its particular application. The integral analysis is intended to provide fundamental global predictions of overall engine and individual component performance which will enhance the overall understanding of each and permit parametric studies to be made. The multidimensional analysis, which is more complicated and expensive to use, will provide details of the flow not provided by the integral analyses such as flow profiles and combustion kinetics.

PROGRESS

Combustor/Inlet Interaction Tests and Modeling: Design, fabrication and installation of the experimental hardware and instrumentation needed for the combustor inlet Mach number, $M_{ci} = 2.5$ tests is complete. Figure 4 is a photograph of the experimental hardware and instrumentation installed in the test cell. Testing has been initiated , some results of which are shown in Fig. 5. Here supersonic annulus wall static pressure distributions for several degrees of supersonic nozzle overexpansion are shown which illustrate the variations in shock strength and axial distance over which they occur. For the cases shown, the air flow split between the supersonic annulus and gas generator simulator is 1:1.

Additional tests with this configuration are currently being made to define the supersonic annulus flow field (or initial conditions) using instrumentation to measure in-stream profiles and wall skin friction forces. A description of the annulus boundary layer depends upon accurate pitot pressure measurements. Efforts to measure the pitot pressure in the annulus at various radial locations have been complicated by high amplitude oscillations in the measured pressure. The fluctuations are as high as 20% of the average measured value. These oscillations are not present in the wall static pressure measurements. In order to determine the cause of the apparent unsteadiness, the following actions have been taken:

(1) all parts of the test rig have been all rigidly attached to the floor;

(2) the downstream ends of the gas generator innerbody and annulus outer wall have been attached by struts to ensure that they vibrate in phase;

(3) the flow blockage has been reduced from 10% to less than 1%;

(4) the pitot probe lengths have been varied;

(5) the pitot probe support struts leading wedge angle has been made as small as possible;

(6) the upstream Reynolds number has been varied;

(7) the digital sampling rate has been increased from 0.4 to 1000 samples/sec;

(8) pressure traces have been obtained on an analog device that is completely independent of the digital data acquisition system;

(9) the effects of pneumatic filtering have been evaluated;

(10) all aspects of the instrumentation have been vigorously examined for origins of extraneous noise;

(11) a small flush-mounted, high response kulite transducer, which can be inserted in the tip of the pitot probe, has been ordered;

(12) statistical analysis of the unsteady data has been pursued; and

(13) the possibility of moisture condensation shock waves introducing the flowfield unsteadiness has been evaluated.

The resolution of the causes of the apparent flowfield unsteadiness, believed at this point to be an accoustic coupling between the pitot probe tip and the pressure transducer, and its effect on the attendant boundary layer description should be resolved by the beginning of June.

Component and Engine Cycle Modeling: An initial model simulating the coaxial mixing and combustion process in the supersonic combustor using a two flame sheet model (H_2, CO) has been developed along with a preliminary analysis for predicting the skin friction and heat transfer losses along the combustor walls. Here, the results of the integral analysis (Ref. 1) are a required input parameter. A number of simplifying assumptions have been made, however, in order to begin the analysis with a reasonably well understood set of parameters. As the analysis progresses, more realistic and, therefore, more complex models will be incorporated.

The analysis of the coaxial mixing and combustion region is used to insure an adequate length of combustor for complete burning and to predict the level of non-uniformity of the combustor exit flow entering the nozzle. The primary goals of the wall boundary layer calculations are predictions of the local heat transfer and skin friction. The heat transfer must be known to design engine cooling systems and structure, and the skin friction in the combustor must be known to calculate overall system performance. The present wall boundary layer analysis includes the important effects of entrainment of combustion products from the coaxial flame into the boundary layer.

Figure 6 is a schematic illustration of the model used to analyze the combustor. The shape and length of the flames are predicted at two operating conditions as shown in Fig. 7. The H_2 flame is about 1 meter long. The edge conditions for the boundary layer calculations were obtained from the coaxial jet mixing and burning code. Figure 8 shows the streamwise variation of the skin friction coefficient and wall heat flux. Here, predicted values of wall skin friction and heat transfer show that both increase with increasing combustor heat release, something heretofore not predicted but observed in past experiments on supersonic combustion ramjet engine combustors (Ref. 13). The sensitivity of the local heat transfer to the local character of the pressure distribution is also illustrated by the steep rise in the air duct ahead of the combustor where a strong shock structure is located. Further details of this effort are given in Refs. 14 and 15.

One of the important complicating features of the flow in the combustor is the recirculation region in the base of the thick "lip" of the gas generator exhaust (Fig. 1). The flow in this region interacts with the hot exhaust jet and the inlet air to determine the pressure and the other flow variables at the beginning of the mixing and burning in the main combustor. The accurate prediction of the subsequent flow in the combustor is clearly dependent upon the determination of good "initial conditions" as a result of an analysis of this base flow.

The present mixing and burning code uses initial conditions generated by a highly simplified treatment of the base flow. We have been working on developing a more adequate analysis. This flow is actually a rather complex member of the family of base flows that has the flow behind a projectile or behind a step as

simpler members. However, the analysis of even those cases has been the subject of study for some years. The more ambitious, modern treatments involve large, expensive numerical calculations. An approach of that type is not suitable for the present purposes, since we need an analysis that can comprise but a part of a bigger analysis. Work at APL in the last several years (Refs. (16) - and (19) has shown the utility of soundly-based approximate methods for many purposes. However, those analyses treat only crudely some of the features of the flow that are important in the current context. Thus, it has been our intent to develop new methods that lie somewhere between those in Refs (16) - (19) and the very elaborate, numerical methods.

The flowfield for a simple, planer base is shown schematically in Fig. 9. We have developed treatments for separate parts of the complete flow. The flow in the upstream boundary layer and some of the inviscid flow above the boundary layer is taken inviscidly through the corner expansion and the lip shock. None but the most complicated existing analyses treat the lip shock at all. The subsequent downstream flow outside of the viscous base region is also treated as inviscid. The viscous treatment of the flow in the base begins at the viscous throat and proceeds upstream. The flow from the viscous throat to the rear stagnation point is analyzed using generalized versions of the methods in Refs. (16) - (19). The flow in the region above the dividing streamline through the rear stagnation point and upstream from the rear stagnation to the downstream end of the constant pressure region is now treated using integrated equations of motion but with the pressure gradient taken as predicted for a centered wave pattern. The flow in the shear layer in the constant pressure region is taken as described by existing analyzed for that simple situation. A unique, composite solution for the whole is selected by requiring continuity of the mass flow in the shear layer from the downstream and upstream proceeding portions of the analysis.

Some comparisons of predictions and experiments are given in Fig. 10-12. Figs. 10 and 12 show centerline pressure distributions at two upstream Mach Numbers in the range of interest. Clearly, the base pressure and the major features of the flow are well predicted. Fig. 11 shows that the important effects of the size of the upstream boundary layer are adequately accounted for.

Inclusion of this revised treatment of the base flow region into the coaxial mixing and combustion analysis is currently underway.

PLANS

Plans are given below for GFY 84 as well as the remainder of GFY 83.

GFY 83

- Complete first CII tests series with $M_{ci} = 2.5$.
- Initiate semi-empirical modeling of CII region.
- Complete revised coaxial mixing, combustion and boundary layer analysis using refined base flow region.
- Continue verification of uni-dimensional combustor and engine models.

GFY 84

- Complete CII tests with $M_{ci} = 1.75$.
- Complete CII tests with $M_{ci} = 3.0$.
- Continue CII modeling (completion expected in GFY 85.
- Continue combustor and engine modeling refinements using available experimental data to verify their accuracy and applicability.

REPORTS/PUBLICATIONS

Progress in each of the above areas is being reported in the JHU/APL Quarterly Progress Reports and by papers at national and international meetings of the AIAA, ISABE, combustion Institute, and JANNAF and their publications. Progress is also being reported during the annual AFOSR contractors meeting and in Annual Interim Reports.

The following reports and articles have been published since the inception of this program in late GFY 1979:

(1) J. A. Schetz, S. Favin and F. S. Billig, "Flowfield Analysis of the HWADM Combustor (U)", (Confidential), APL/JHU Quarterly Progress Report RQR/79-3, #11, October 1979.

(2) R. D. Stockbridge and P. J. Waltrup, "Preliminary Plans for the IRDCR Combustor/Inlet Interaction Tests, (Unclassified) APL/JHU Quarterly Progress Report RQR/79-4 (Confidential), #7, January 1980.

(3) J. A. Schetz, S. Favin and F. S. Billig, "Boundary Layer Analysis of the HWADM Combustor",APL/JHU Quarterly Progress Report RQR/80-1 (Confidential), #10, April 1980.

(4) J. A. Schetz, S. Favin and F.S. Billig, "Analysis of Flow in the HWADM Combustor", (Unclassified) APL/JHU Quarterly Progress Report RQR/80-3 (Confidential), #7, October 1980.

(5) J. A. Schetz, F. S. Billig and S. Favin, "Analysis of Mixing and Combustion in a Scramjet Combustor with a Coaxial Fuel Jet (U)". AIAA/ASME/SAE 16th Joint Propulsion Conference, AIAA Preprint 80-1256, June 1980.

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PRINCIPAL PERSONNEL

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APL/JHU
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Richard D. Stockbridge
Associate Engineer
APL/JHU
Ph.D. Candidate - U. of Md.
4 major publications

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2. P. J. Waltrup, F. S. Billig, R. C. Orth, S. E. Grenleski, J. A. Funk and G. L. Dugger, "Summary Report of Connected-Pipe SCRAM Tests," (U) (Confidential), TG-1304, The Johns Hopkins University Applied Physics Laboratory, Laurel, Maryland, April, 1977.

3. P. J. Waltrup, F. S. Billig, J. A. Funk, and G. L. Dugger, "Development and Testing of Hypersonic Ramjet Engines," (U) (Confidential), presented at the 1974 JANNAF Propulsion Meeting, San Diego, Calif., October 22-24, 1974, also CPIA Publication 260, Vol. II, Part 1, February, 1975, pp. 189-212.

4. F. S. Billig, G. L. Dugger, P. J. Waltrup, "Inlet-Combustor Interface Problems in Scramjet Engines," invited paper presented at the 1st International Symposium on Air Breathing Engines, Marseille, France, June 1972.

5. P. J. Waltrup and F. S. Billig, "The Structure of Shock Waves in Cylindrical Ducts," AIAA Journal, Vol. 11, No. 10, October 1973.

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11. V. Agosta and S. Hammer, "Scramjet Nozzle Analysis," PSI Report 70-1, Propulsion Sciences, Inc. Melville, N. Y., February 1970.

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15. J. A. Schetz, F. S. Billig, and S. Favin, "Scramjet Combustor Wall Boundary Layer Analysis (U)," AIAA/ASME/SAE 17th Joint Propulsion Conference, AIAA Preprint 81-1434, July 1981.

16. J. A. Schetz and F. S. Billig, "Approximate Analysis of Base Burning in Supersonic Flow," Progress in Astronautics and Aeronautics: Aerodynamics of Base Combustion,Vol. 40, edited by S.N.B. Murthy, AIAA, New York, 1976, pp. 385-405.

17. J. A. Schetz and F. S. Billig, "Simplified Analysis of Supersonic Base Flows Including Injection and Combustion,"" AIAA Journal, Vol. 14, Jan. 1976, pp. 7-8.

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19. J. A. Schetz, F. S. Billig and S. Favin, Analysis of Base Drag Reduction by Base and/or External Burning, Applied Physics Laboratory, Johns Hopkins University, Laurel, Maryland, AIAA Journal, Vol. 19, No. 9, September, 1981.

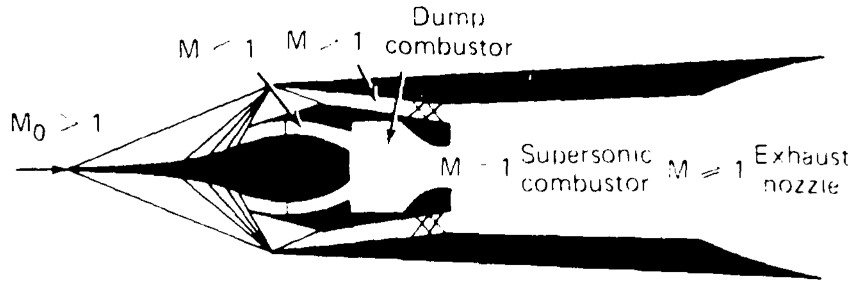

Fig. 1 Schematic of dual combustion ramjet engine.

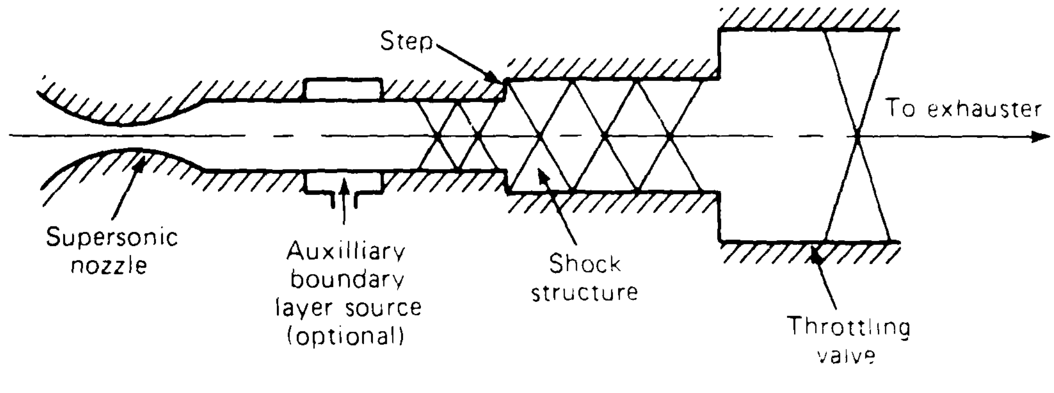

Fig. 2 Schematic of combustor/inlet interaction test apparatus for scramjet.

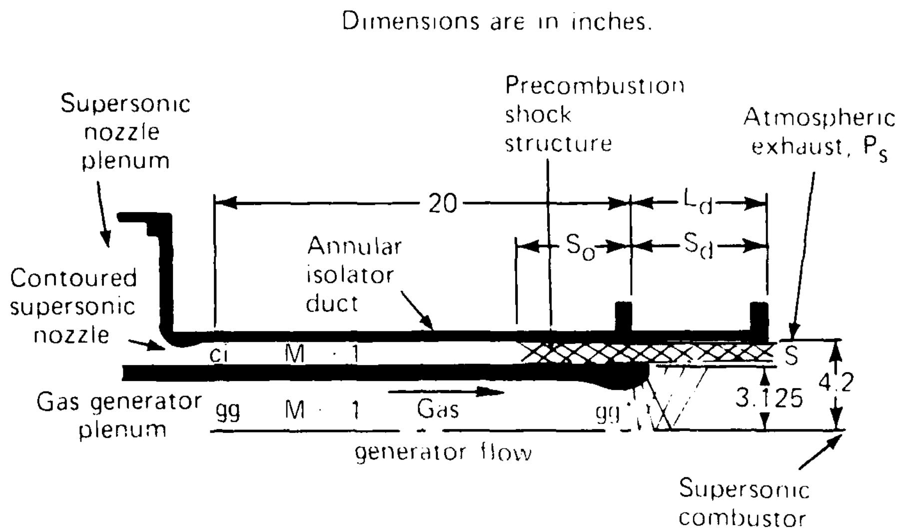

Fig. 3 Schematic of combustor/inlet interaction hardware for DCR engine.

Fig. 4 Combustor/inlet interaction test setup.

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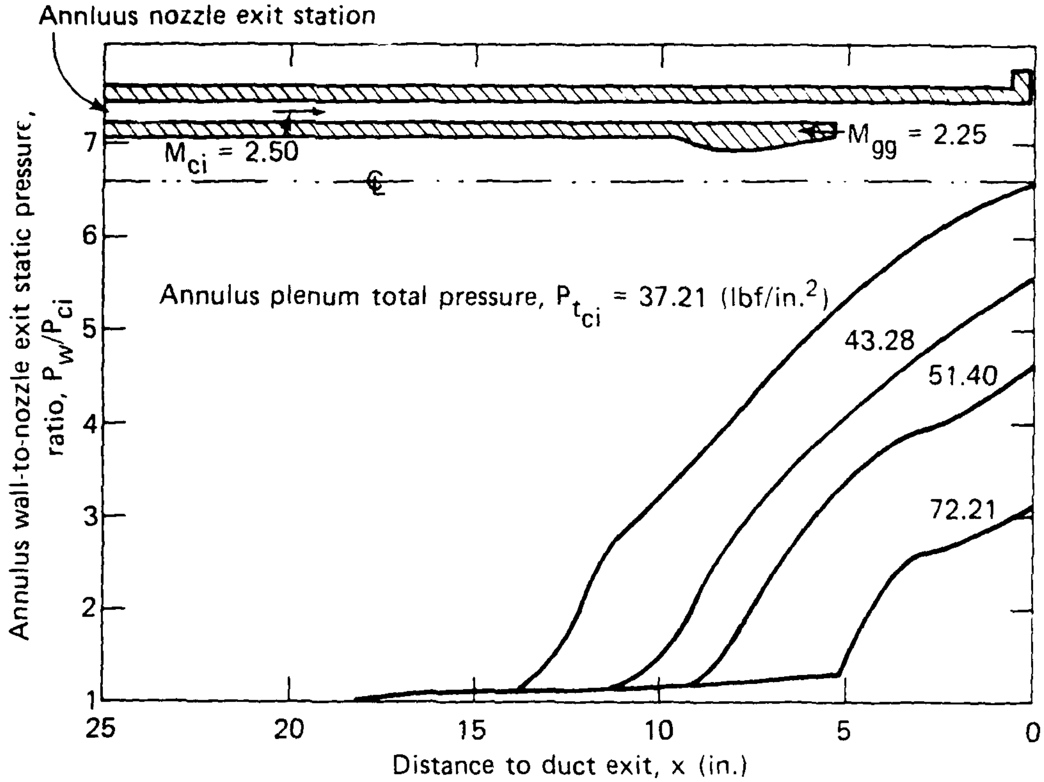

Fig. 5 Annulus outer wall static pressure distributions.

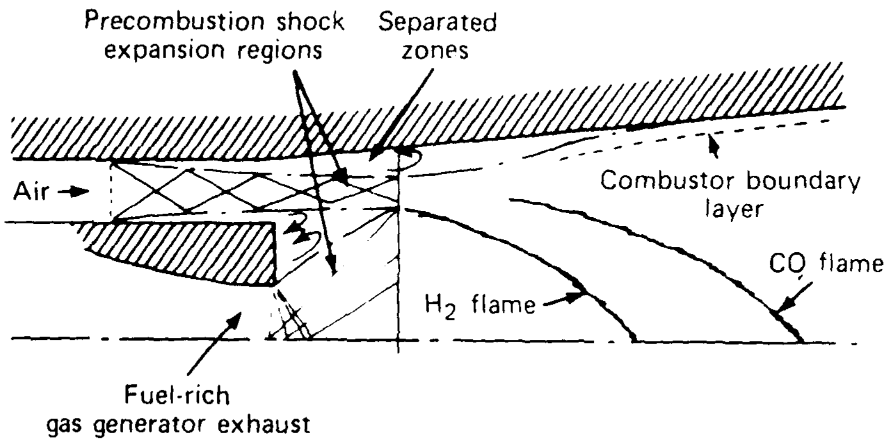

Fig. 6 Model of supersonic combustor.

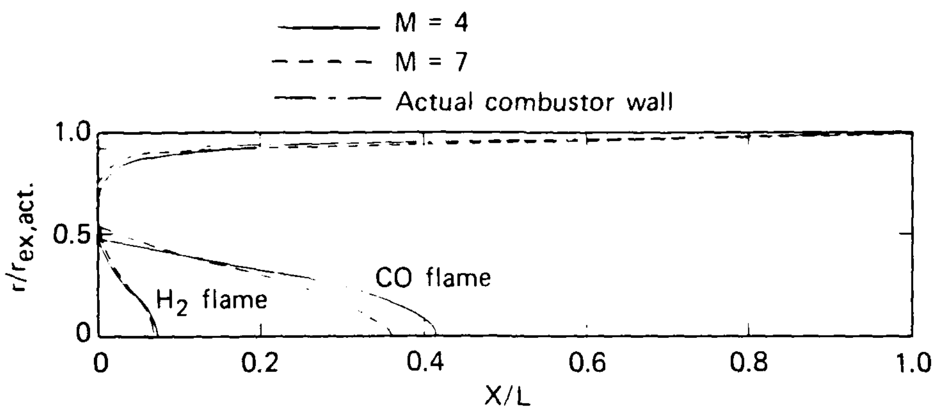

Fig. 7 **Predicted combustor and flame sheet contours for M_0 = 4 and 7 flight with ER = 0.5.**

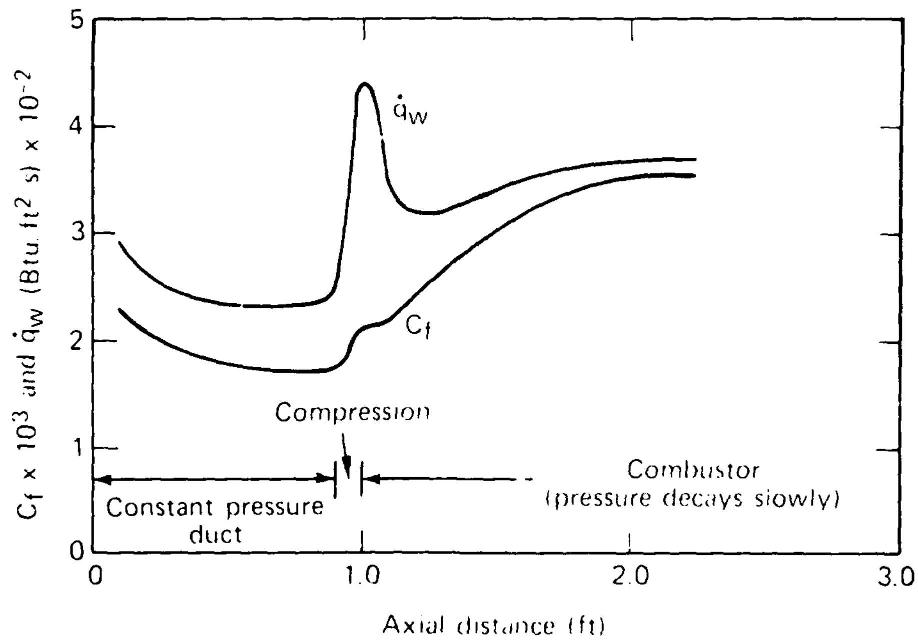

Fig. 8 **Combustor wall skin friction coefficient and heat flux distributions for M_0 = 7 flight for ER = 0.5.**

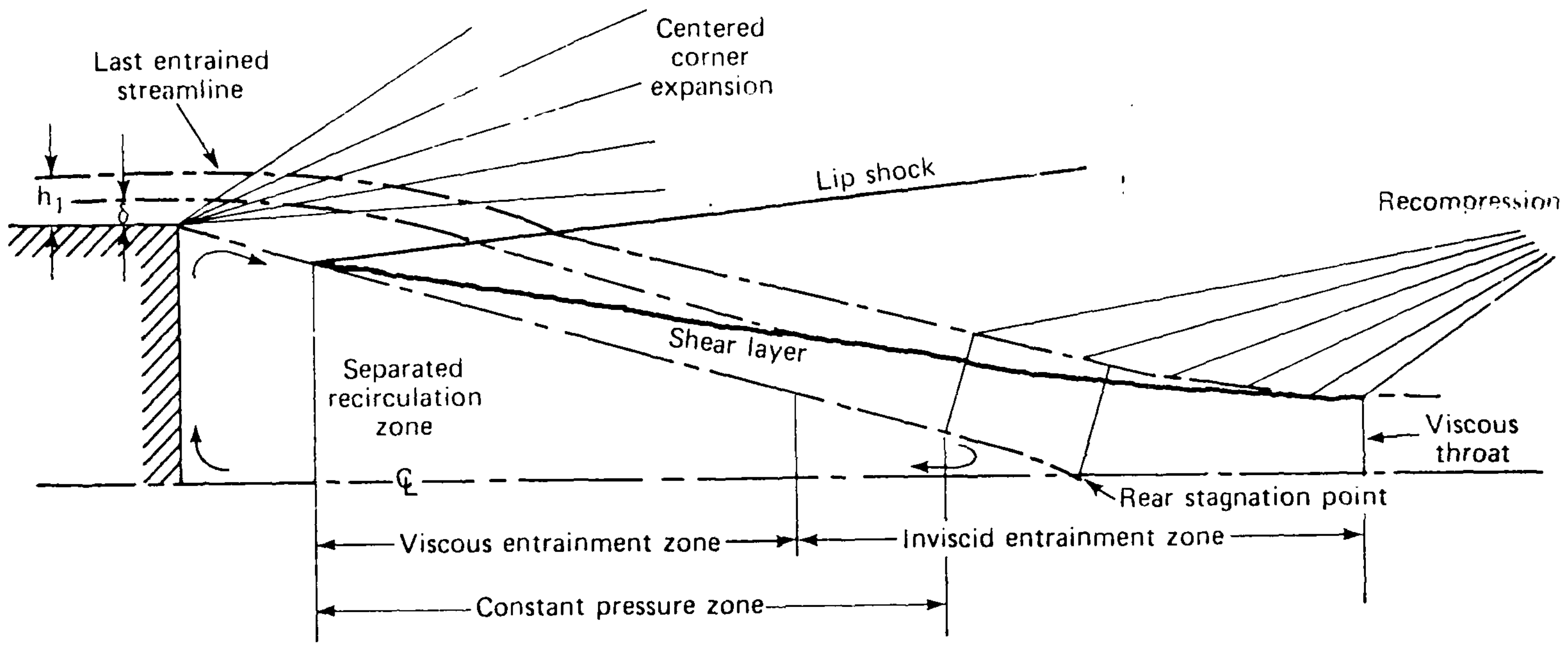

Fig. 9 Schematic illustration of base flow entrainment model.

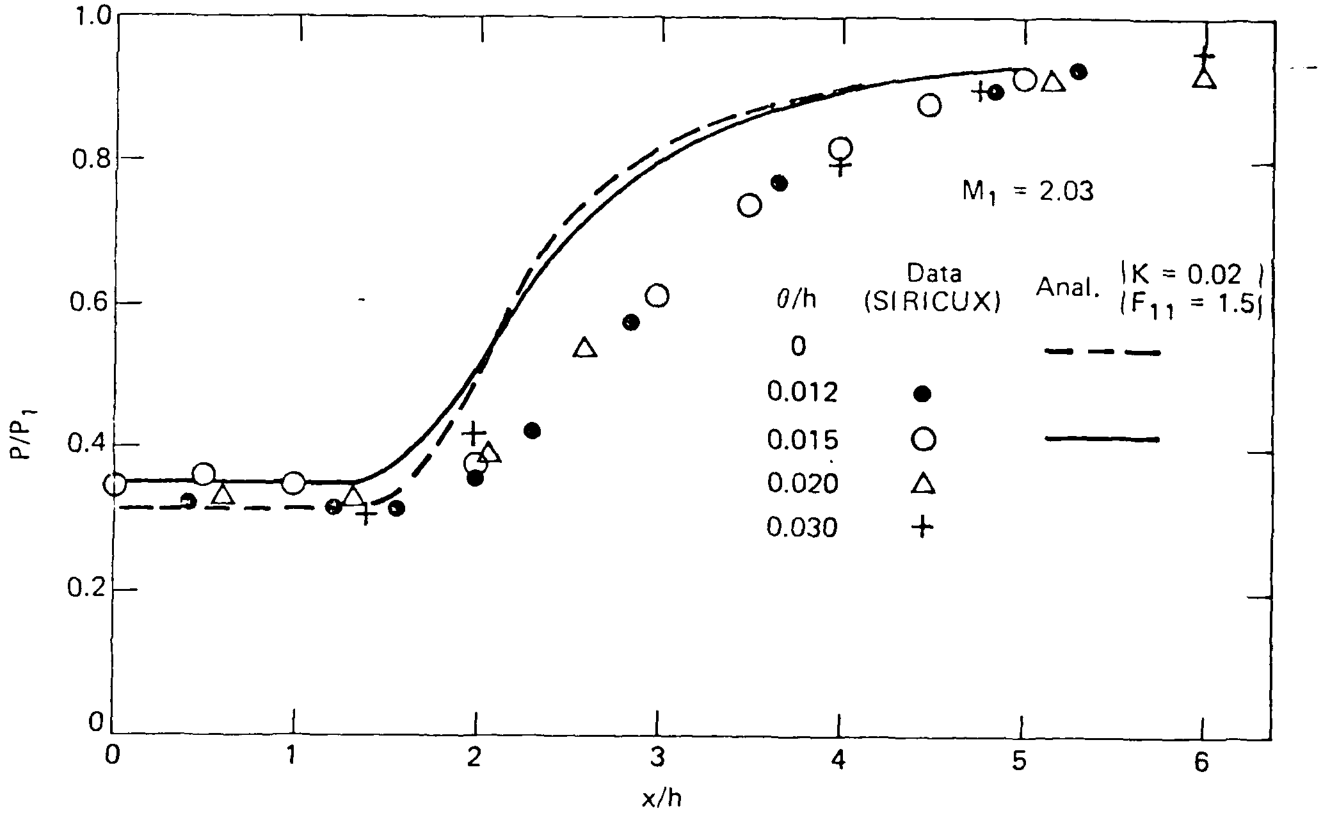

Fig. 10 Prediction and experiment for pressure distribution behind a base at $M_1 = 2.03$.

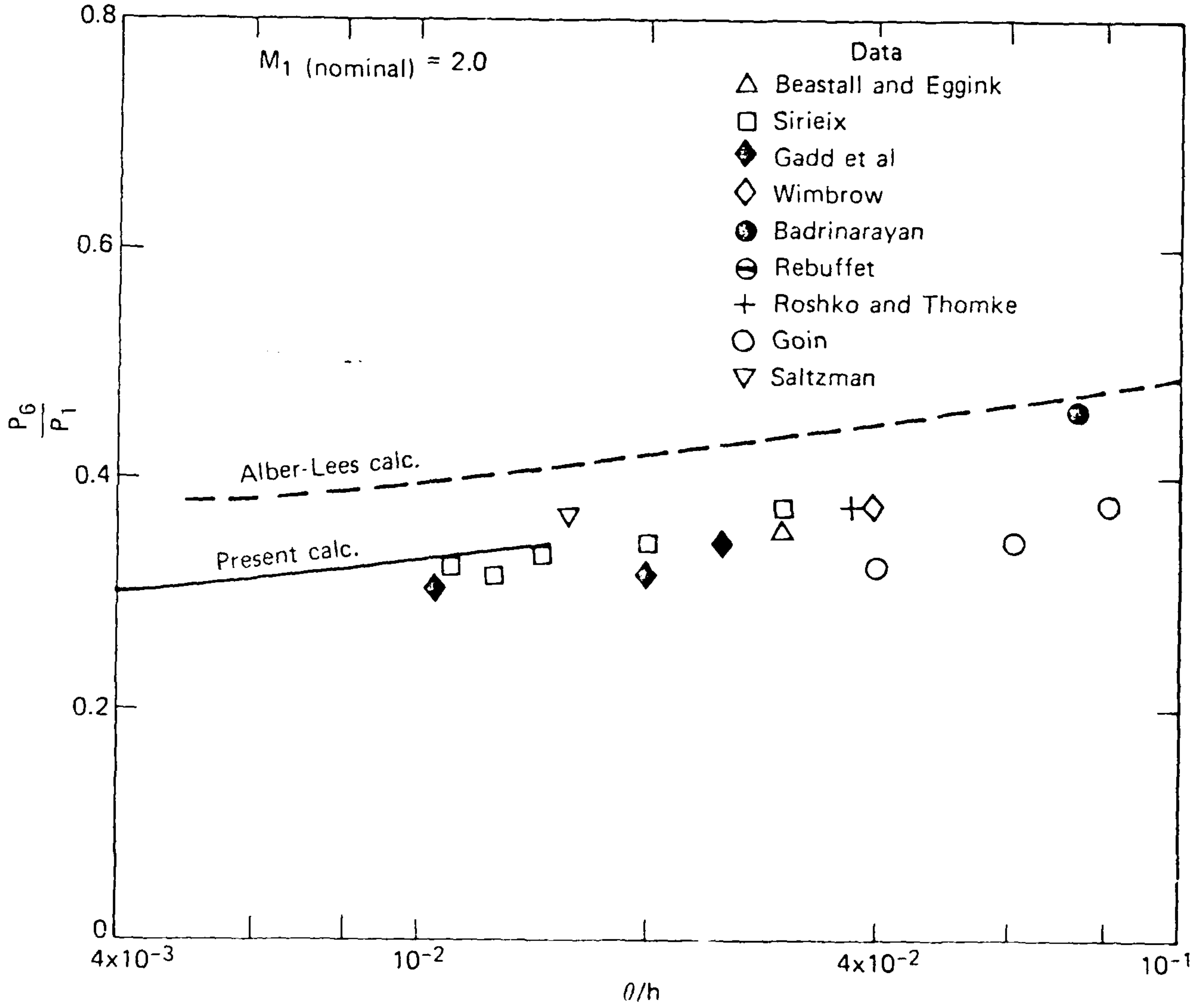

Fig. 11 Effect of upstream boundary layer momentum thickness on base pressure.

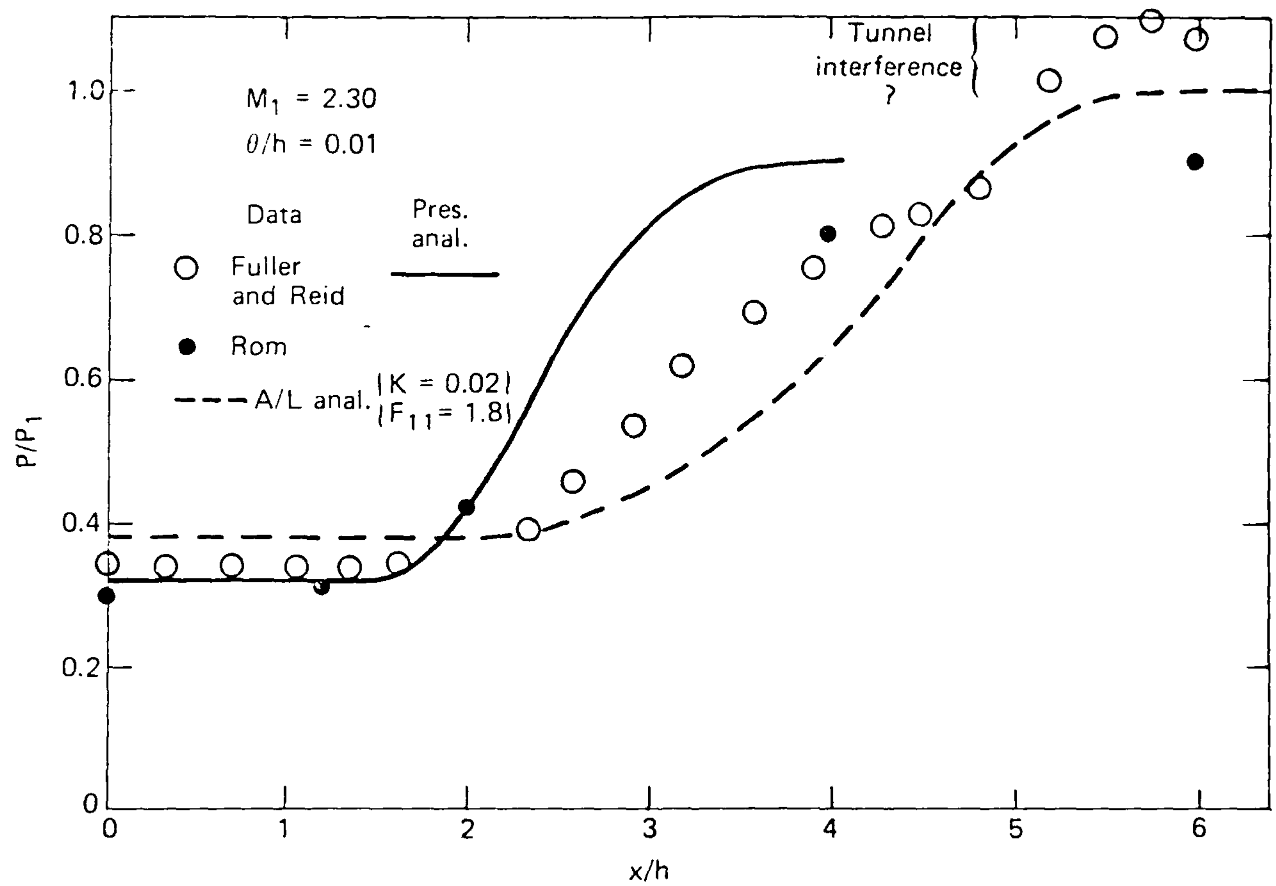

Fig. 12 Predictions and experiments for pressure distribution behind a base at M_1 = 2.30.